

Sensitivity of the T2HKK experiment to the non-standard interaction

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Abstract

If the flavor dependent non-standard interactions (NSI) in neutrino propagation exist, then the matter effect is modified and the modification is parametrized by the dimensionless parameter $\epsilon_{\alpha\beta}$ ($\alpha, \beta = e, \mu, \tau$). In this paper we discuss the sensitivity of the T2HKK experiment, whose possibility is now seriously discussed as a future extension of the T2K experiment, to such NSI. On the assumption that $\epsilon_{\alpha\mu} = 0$ ($\alpha = e, \mu, \tau$) and $\epsilon_{\tau\tau} = |\epsilon_{e\tau}|/(1 + \epsilon_{ee})$, which are satisfied by other experiments to a good approximation, we find that, among the possible off-axis flux configurations of 1.3° , 1.5° , 2.0° and 2.5° , the case of the off-axis angle 1.3° gives the highest sensitivity to ϵ_{ee} and $|\epsilon_{e\tau}|$. Our results show that the 1.3° off-axis configuration can exclude NSI for $|\epsilon_{ee}| \gtrsim 1$ or $|\epsilon_{e\tau}| \gtrsim 0.2$ at 3σ . We also find that in the presence of NSI, T2HKK (for the off-axis angle 1.3°) has better sensitivity to the two CP phases (δ_{CP} and $\arg(\epsilon_{e\tau})$) than DUNE. This is because of the synergy between the two detectors i.e., one at Kamioka and one at Korea. T2HKK has better sensitivity to the CP phases than the atmospheric neutrino experiment at Hyperkamiokande in inverted hierarchy, but in normal hierarchy the atmospheric neutrino experiment has the best sensitivity to the CP phases.

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I. INTRODUCTION

It has been established by the successful experiments in the past that neutrinos have masses and mixings [1]. The three mixing angles θ_{12} , θ_{13} , θ_{23} and two mass-squared differences Δm_{31}^2 , Δm_{21}^2 in the standard three flavor neutrino oscillation framework are measured as: $(\Delta m_{21}^2, \sin^2 2\theta_{12}) \simeq (7.5 \times 10^{-5} \text{eV}^2, 0.86)$, $(|\Delta m_{31}^2|, \sin^2 2\theta_{23}) \simeq (2.4 \times 10^{-3} \text{eV}^2, 1.0)$, $\sin^2 2\theta_{13} \simeq 0.09$. The remaining unknowns are the value of the Dirac CP phase δ_{CP} , the sign of Δm_{31}^2 (the mass hierarchy i.e., normal or inverted) and the octant of θ_{23} (the sign of $\pi/4 - \theta_{23}$ i.e., lower or higher). It is expected that these unknowns will be determined by the future neutrino oscillation experiments, particularly the accelerator based long-baseline neutrino experiments [2, 3]. These experiments in the future can not only measure the oscillation parameters in the standard three flavor mixing scenario but also probe the new physics by looking at the deviation from the standard three flavor neutrino mixing framework.

Flavor-dependent neutral current neutrino Non-Standard Interactions (NSI) [4–6] have been studied as one of the new physics candidates which can be searched at the future neutrino experiments [7, 8]. In the presence of these NSI the neutrino propagation feels the extra contribution to the matter effect and hence long-baseline experiments with a longer baseline length L (typically $L \gtrsim 1000$ km) and the atmospheric neutrino experiments are expected to have sensitivity to the neutral current NSI. Recent studies of neutral current NSI in long-baseline and atmospheric neutrino experiments can be found in Ref. [9–28].

The possibility of a second detector in Korea for the T2K [29] experiment was discussed in the past [30–45]. Recently there has been a renewed interest in the idea of placing the second detector in Korea as a part of the T2HK plan [2], and the plan with the second detector in Korea is now called the T2HKK project [46]. The original plan of the T2HK project is to build a large tank of water Čerenkov detector of volume 560 kt at the Kamioka site. Under the T2HKK project, there will be two tanks of equal volume each of 280 kt instead of building a single tank and then one of the tanks will be built in Korea. Depending on the location of the second detector in Korea, one has different options for the flux in terms of the off-axis angle. According to the HK collaboration, the flux options of 1.3° , 1.5° , 2.0° and 2.5° off-axis configurations are under consideration at present [47]. In the T2HKK project, there are some discussions on which location is the most advantageous from the physics point of view and the report from the HK collaboration regarding this is under preparation. In this

paper for the first time we study the sensitivity of T2HKK to NSI and discuss the result of optimization for the NSI parameters ϵ_{ee} and $|\epsilon_{e\tau}|$ with respect to the different flux options. We also compare its sensitivity with that of DUNE and the atmospheric neutrino experiment at Hyperkamiokande (HK) [48]. While a similar analysis was done in the past [41], the new points in the present paper are the optimization with respect to the location, which can be expressed in terms of the off-axis angle, and the comparison of the sensitivity with DUNE [3] and the atmospheric neutrino at HK.[48]

This paper is organized as follows. In Section II, we describe the constraints on NSI in propagation. In Section III, we study the sensitivity of the T2HKK experiment to NSI. In Section IV, we draw our conclusions.

II. PRELIMINARIES

A. Nonstandard interactions

Let us start with the effective flavor-dependent neutral current neutrino non-standard interactions in propagation given by

$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\epsilon_{\alpha\beta}^{ff'P}G_F(\bar{\nu}_{\alpha L}\gamma_{\mu}\nu_{\beta L})(\bar{f}_P\gamma^{\mu}f'_P), \quad (1)$$

where f_P and f'_P stand for fermions with chirality P and $\epsilon_{\alpha\beta}^{ff'P}$ is a dimensionless constant which is normalized by the Fermi coupling constant G_F . The presence of NSI in Eq.(1) modifies the MSW potential in the flavor basis from

$$\sqrt{2}G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (2)$$

to

$$\mathcal{A} \equiv \sqrt{2}G_F N_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}, \quad (3)$$

where $\epsilon_{\alpha\beta}$ is defined by

$$\epsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \frac{N_f}{N_e} \epsilon_{\alpha\beta}^f. \quad (4)$$

N_f ($f = e, u, d$) stands for number densities of fermions f . Here we defined the NSI parameters as $\epsilon_{\alpha\beta}^{fP} \equiv \epsilon_{\alpha\beta}^{ffP}$ and $\epsilon_{\alpha\beta}^f \equiv \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$. In the three flavor neutrino oscillation framework with NSI, the neutrino evolution is given by the Dirac equation:

$$i \frac{d}{dx} \begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix} = [U \text{diag}(0, \Delta E_{21}, \Delta E_{31}) U^{-1} + \mathcal{A}] \begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix}, \quad (5)$$

where U is the leptonic mixing matrix defined by

$$U \equiv \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{13} \end{pmatrix}, \quad (6)$$

and $\Delta E_{jk} \equiv \Delta m_{jk}^2/2E \equiv (m_j^2 - m_k^2)/2E$, $c_{jk} \equiv \cos \theta_{jk}$, $s_{jk} \equiv \sin \theta_{jk}$.

As far as the neutrino oscillation on the Earth is concerned, we have the following limits on $\epsilon_{\alpha\beta}$ from the compilation of various neutrino data at 90% C.L.: [49, 50]

$$\begin{pmatrix} |\epsilon_{ee}| < 4 \times 10^0 & |\epsilon_{e\mu}| < 3 \times 10^{-1} & |\epsilon_{e\tau}| < 3 \times 10^0 \\ & |\epsilon_{\mu\mu}| < 7 \times 10^{-2} & |\epsilon_{\mu\tau}| < 3 \times 10^{-1} \\ & & |\epsilon_{\tau\tau}| < 2 \times 10^1 \end{pmatrix}. \quad (7)$$

It was pointed out in Refs. [51, 52] that the high-energy atmospheric neutrino data, where the matter effects are dominant, are consistent with NSI only when the following equality is approximately satisfied:

$$\epsilon_{\tau\tau} = \frac{|\epsilon_{e\tau}|^2}{1 + \epsilon_{ee}}. \quad (8)$$

If Eq. (8) is satisfied, then $\epsilon_{\tau\tau}$ can be eliminated. Furthermore, we have

$$\left| \frac{\epsilon_{e\tau}}{1 + \epsilon_{ee}} \right| \lesssim 0.6 \quad \text{at 90\% C.L.,} \quad (9)$$

from the atmospheric neutrino data of Superkamiokande [14].

From the above two constraints (7) and (8), the following ansatz is a good approximation to analyze the sensitivity to NSI:

$$\mathcal{A} = \sqrt{2}G_F N_e \begin{pmatrix} 1 + \epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2/(1 + \epsilon_{ee}) \end{pmatrix}. \quad (10)$$

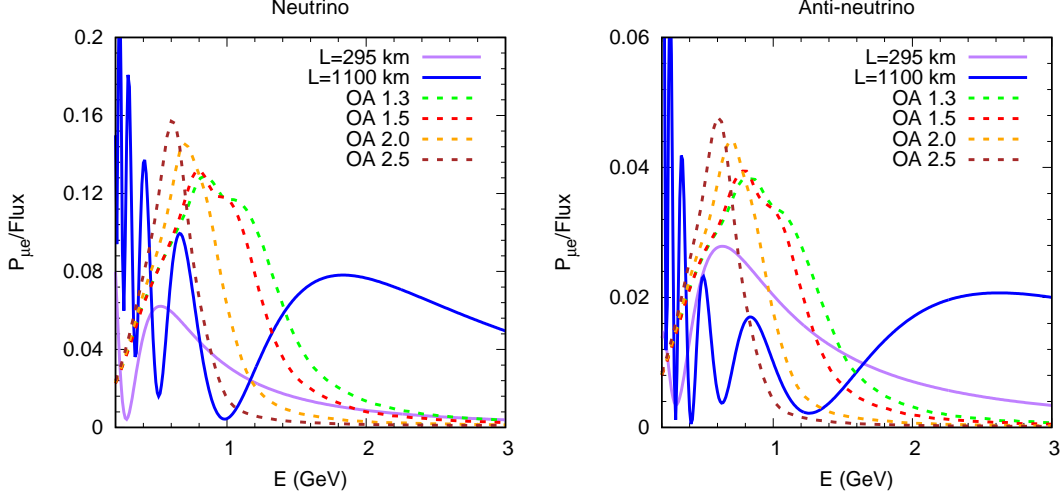


FIG. 1: The flux (dashed curves) at different off-axis angles and the appearance oscillation probabilities (solid curves) at Kamioka ($L=295$ km) and in Korea ($L=1100$ km) in the standard oscillation scenario in normal hierarchy. The left (right) panel is for neutrinos (antineutrinos). The baseline length $L=1088$ km at an angle 1.3° is slightly different from $L=1100$ km, but the difference between the oscillation probabilities at $L=1088$ km and at $L=1100$ km is invisibly small.

The allowed region in the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane at 90% C.L., is given by the following:

$$-4 \lesssim \epsilon_{ee} \lesssim 4, \quad |\epsilon_{e\tau}| \lesssim 3, \quad \left| \frac{\epsilon_{e\tau}}{1 + \epsilon_{ee}} \right| \lesssim 0.6. \quad (11)$$

B. The T2HKK experiment

The T2HKK experiment is a proposal for the future extension of the T2K experiment. In this proposal, a water Čerenkov detector is placed not only in Kamioka (at a baseline length $L = 295$ km) but also in Korea (at $L \simeq 1100$ km), whereas the power of the beam at J-PARC in Tokai Village is upgraded to 1.3 MW. As in the T2K experiment, it is assumed that T2HKK uses an off-axis beam at a 2.5° angle between the directions of the decaying charged pions and neutrinos, and the neutrino energy spectrum has a peak approximately at 0.6 GeV. This off-axis beam at an angle 2.5° reaches Korea and the corresponding off-axis angle on the surface in Korea ranges from 1.3° to 2.5° with the baseline 1088 km (for 1.3°) to 1100 km (for 1.5° , 2.0° and 2.5°), depending on the location of the detector in Korea. The flux and the appearance oscillation probabilities for neutrinos and antineutrinos at various off-axis angles in normal hierarchy are shown in Fig. 1. As we can see from Fig. 1, the first

oscillation maximum occurs at $E \simeq 1.8$ (2.6) GeV, whereas the second one appears at $E \simeq 0.7$ (0.8) GeV for neutrinos (antineutrinos). From Fig. 1 we observe the following:

- Among the different off-axis fluxes, the flux corresponding to the lowest off-axis angle peaks at the highest energy and the flux at the highest off-axis angle peaks at the lowest energy.
- The height of the flux corresponding to the lower off-axis angle is more as compared with the height of the flux corresponding to the higher off-axis angle.
- The off-axis fluxes corresponding 2.5° and 2.0° mainly cover the second oscillation maxima for $L=1100$ km while the off-axis fluxes corresponding to 1.3° and 1.5° also cover a part of the first oscillation maxima.

III. SENSITIVITY OF T2HKK TO ϵ_{ee} AND $|\epsilon_{e\tau}|$

In this section we discuss the sensitivity of the T2HKK experiment to the non-standard interaction in propagation with the ansatz (10). For comparison, we also study sensitivity of the DUNE [3] and the atmospheric neutrino experiment at HK [48]. Since $\epsilon_{\tau\tau}$ is expressed in terms of ϵ_{ee} and $|\epsilon_{e\tau}|$, the only new degrees of freedom are ϵ_{ee} , $|\epsilon_{e\tau}|$ and $\arg(\epsilon_{e\tau})$. First of all, in sect. III A, assuming that the Nature is described by the standard three-flavor scheme, we discuss the bounds on ϵ_{ee} and $|\epsilon_{e\tau}|$. In our analysis we assume that the true numbers of events are those of the standard three-flavor scenario, and the test numbers of events are those with NSI. We discuss the region of the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane in which T2HKK can exclude the hypothesis with NSI. Secondly, in sect. III B, assuming that NSI exists, we consider whether the two complex phases δ_{CP} and $\arg(\epsilon_{e\tau})$ can be determined separately.

The neutrino flux of the T2HKK experiment in Korea is taken from Ref. [47]. To calculate the event rates for the T2HKK setup we proceed in the following way. First we have matched the number of events corresponding to the T2HK setup as given in Ref. [2] taking the 2.5° off-axis flux. The detector volume in this case is 560 kt. Then we scale these number of events for the Korean baseline corresponding to different off-axis configurations. For T2HKK project we have taken 280 kt detector both at Kamioka and Korea. Note that as we have taken the backgrounds corresponding to the T2HK setup and scale them down for the Korean baseline, the neutral current π^0 backgrounds at the high energies are ignored and thus our

Off-axis degree	1.3°	1.5°	2.0°	2.5°
Neutrinos	515	438	368	309
Antineutrinos	39	34	25	17

TABLE I: The numbers of appearance events for neutrino and antineutrinos expected at the second detector in Korea. $\theta_{23} = \pi/4$, $\delta = -\pi/2$ with normal hierarchy is assumed.

results of T2HKK may be optimistic. For T2HKK setup we have taken a total integrated beam-power of 15.6×10^{21} pot with 10^{21} pot/year. Thus it corresponds to 15.6 years running of the beam. For T2HKK we have taken an overall systematic error of 3.3% for both appearance and disappearance channel in neutrino mode and 6.2% (4.5%) for appearance (disappearance) channel in antineutrino mode. The systematic error is the same for both the signal and the background. For DUNE we have taken a flux of beam-power 1.2 MW with 10^{21} pot/year and 34 kt liquid argon detector. In our analysis we have considered a 10 years running of DUNE unless otherwise mentioned. The number of events are taken from Ref. [3]. The systematic error for DUNE is 2% (10%) for appearance channel and 5% (15%) for disappearance channel corresponding to the signal (the background). The systematic errors in neutrino and antineutrino mode are the same for DUNE. The simulations of T2HKK and DUNE have been performed with the softwares GLoBES [53, 54] and MonteCUBES [55].

Assuming the operation with $\nu:\bar{\nu} = 1:1$, as well as the oscillation parameters $\theta_{23} = \pi/4$, $\delta_{CP} = -\pi/2$ with normal hierarchy, the expected numbers of appearance events in Korea, are shown in Table I, while those at Kamioka are 3219 neutrinos and 420 antineutrinos. The expected numbers of appearance events at DUNE are 1897 neutrinos and 229 antineutrinos. Simulation of the atmospheric neutrino at HK is done with the codes which were used in Refs. [14, 56–58] and is described in detail in Ref. [14]. We assume here the data size from the HK atmospheric neutrino experiment for 15 years with 560 kt fiducial volume.

A. Bounds on ϵ_{ee} and $|\epsilon_{e\tau}|$

Firstly, let us discuss the case of the region $(\epsilon_{ee}, |\epsilon_{e\tau}|)$, in which we can test the difference between NSI with ansatz (10) and the standard three-flavor scheme. Here, we take the

best-fit values for most of the standard oscillation parameters as the reference values:¹

$$\begin{aligned}
\sin^2(2\bar{\theta}_{12}) &= 0.87 \\
\sin^2(2\bar{\theta}_{23}) &= 1.0 \\
\sin^2(2\bar{\theta}_{13}) &= 0.09 \\
\Delta\bar{m}_{21}^2 &= 7.9 \times 10^{-5} \text{eV}^2 \\
\Delta\bar{m}_{32}^2 &= 2.4 \times 10^{-3} \text{eV}^2 \\
\bar{\delta}_{\text{CP}} &= -\frac{\pi}{2}
\end{aligned} \tag{12}$$

The results are shown in Fig. 2, where the curves are drawn at 3σ ($\Delta\chi^2 = 11.83$ for 2 degrees of freedom). Also the bounds on ϵ_{ee} and $|\epsilon_{e\tau}|$ at 90% C.L., are summarized in Table II. NSI with the ansatz (10) can be distinguished from the standard three-flavor scheme outside the curves. For comparison, we have also showed the excluded regions by the long-baseline experiment DUNE, the atmospheric neutrino experiment HK and T2HK with the detector of volume 560 kt at Kamioka only. From Fig. 2, we observe that the case at off-axis angle 1.3° has the highest sensitivity to $(\epsilon_{ee}, |\epsilon_{e\tau}|)$. This is because the number of events is the largest at off-axis angle 1.3° , as we can see from Table I. The sensitivity at the 1.5° off-axis is similar as that of 1.3° while the sensitivities at 2.0° and 2.5° are worse than sensitivities at 1.3° and 1.5° . If we compare the sensitivity of the T2HKK with T2HK, then we find that T2HKK is far more powerful than T2HK in terms of constraining the value of the NSI parameters. These results are true for both normal and inverted hierarchies. The sensitivity of DUNE to NSI is comparable to T2HKK at 1.3° for normal hierarchy and better in inverted hierarchy. The sensitivity of HK atmospheric neutrino experiment is the highest for both the hierarchies.

In Fig. 3, χ^2 to exclude a particular choice $(\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)$ is plotted as a function of the running time. Here for comparison we have extended the DUNE runtime to 15 years. From the figures we see that the sensitivity in normal hierarchy is better than inverted hierarchy. We also see that T2HKK at off-axis angle 1.3° can exclude the case with $(\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)$ at 2σ within its proposed run-time. Similar as that of Fig. 2, the sensitivity of 1.5° is comparable with 1.3° and the sensitivities at 2.0° and 2.5° are poor. The significance

¹ The oscillation parameters with bars (without bars) stands for the true (test) value throughout this paper.

Experiment	ϵ_{ee}	$ \epsilon_{e\tau} $
T2HK	-4 to +4	< 0.9
T2HKK(OA1.3 $^\circ$)	-1.4 to 1	< 0.24
T2HKK(OA1.5 $^\circ$)	-0.2 to 0.2	< 0.02
T2HKK(OA2.0 $^\circ$)	-0.3 to 0.3	< 0.03
T2HKK(OA2.5 $^\circ$)	-1.4 to 0.6	< 0.2
DUNE	-0.1 to 0.4	< 0.04
atm(HK)	-0.1 to 0.1	< 0.035

TABLE II: The bounds on ϵ_{ee} and $|\epsilon_{e\tau}|$ at 90% C.L., by each experiment in the case of normal hierarchy.

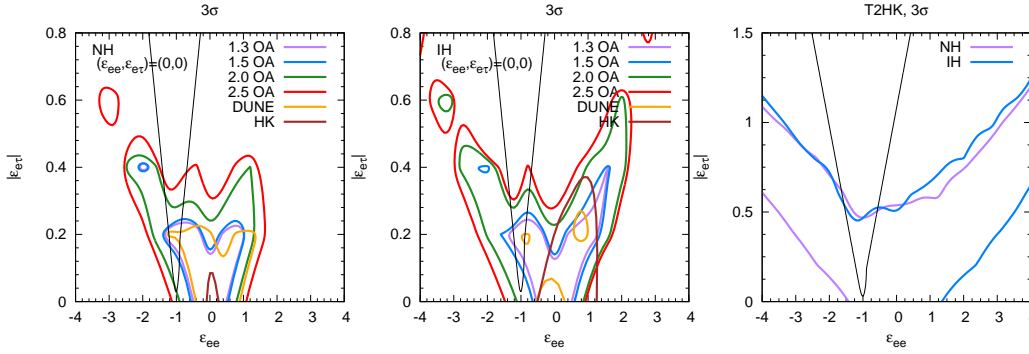


FIG. 2: The excluded region in the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane. The hypothesis with NSI is excluded at 3σ outside each curve. The thin solid diagonal straight line stands for the bound from the current atmospheric data by Superkamiokande. Upper left pane: Normal mass hierarchy. Upper right panel: Inverted mass hierarchy. Lower panel: The bounds from T2HK with the detector of volume 560 kt at Kamioka only.

to exclude NSI is the best for the HK atmospheric neutrino experiment and it is followed by DUNE. Notice that the sensitivity of T2HK with the detector at Kamioka only has poor sensitivity, and therefore the second detector in Korea greatly improves its sensitivity at all the off-axis angles.

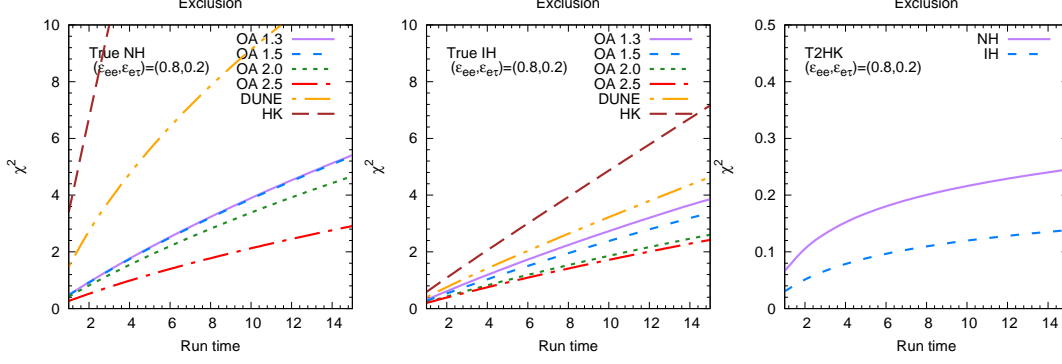


FIG. 3: χ^2 to exclude $(\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)$ as a function of the running time. Upper right panel: Inverted mass hierarchy. Lower panel: The bounds from T2HK with the detector at Kamioka only.

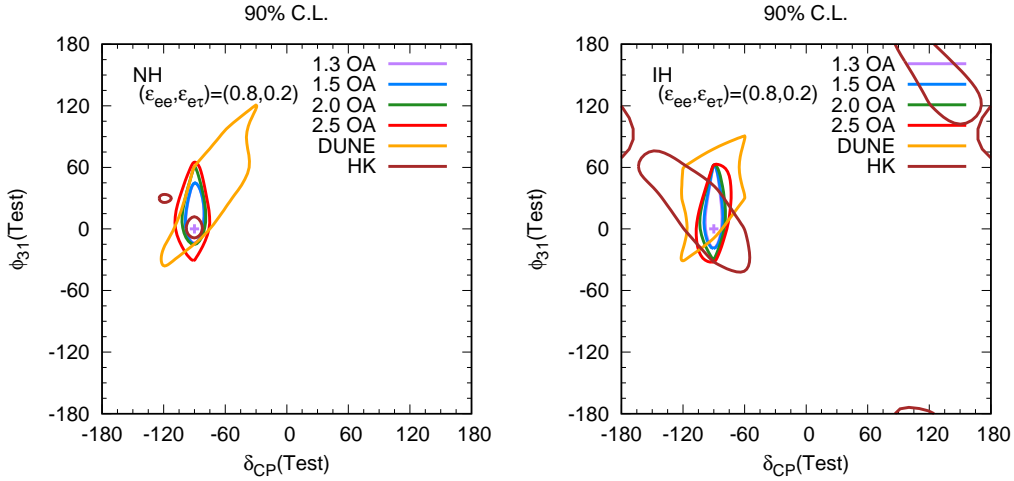


FIG. 4: The correlation between δ_{CP} and $\phi_{31} \equiv \arg(\epsilon_{e\tau})$ for normal hierarchy (left panel) and inverted hierarchy (right panel). The true value is $(\bar{\delta}_{CP}, \bar{\phi}_{31}) = (-\pi/2, 0)$.

B. CP violating phases

Next let us consider the implication to the T2HKK experiment in the case with an affirmative result of NSI. As a reference value for NSI we take $(\bar{\epsilon}_{ee}, |\bar{\epsilon}_{e\tau}|) = (0.8, 0.2)$, which lies outside each exclusion curve in the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane at 90% C.L.²

The ansatz (10) contains the two phases δ_{CP} and $\arg(\epsilon_{e\tau})$. In the presence of NSI, it is important how precisely we can determine these two phases. So we study the correlation

² Notice that Fig. 2 is depicted for 3σ and the allowed region at 90% C.L., is smaller than that at 3σ .

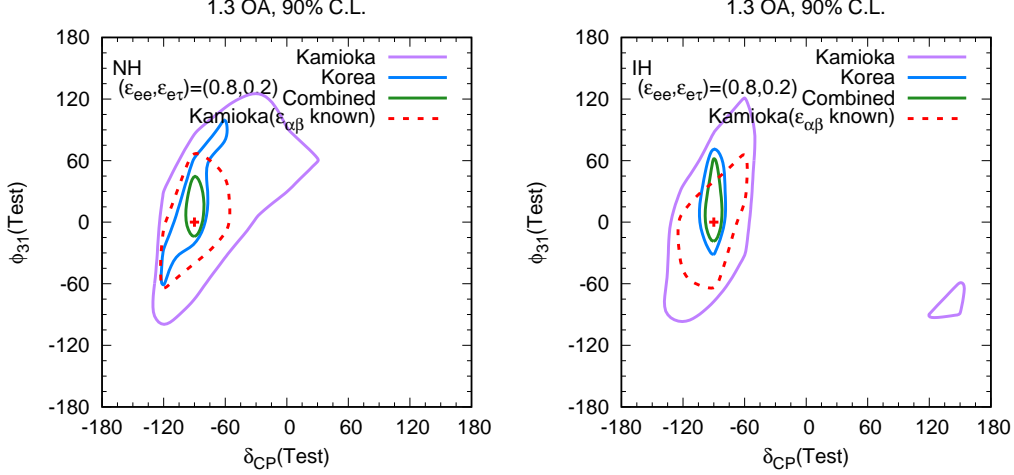


FIG. 5: The correlation between δ_{CP} and $\phi_{31} \equiv \arg(\epsilon_{e\tau})$ for normal hierarchy (left panel) and inverted hierarchy (right panel) at the off-axis angle 1.3° . The true value are $\bar{\phi}_{31} = 0$ and $\bar{\delta}_{\text{CP}} = -\pi/2$. The dotted curves, which are given for the detector at Kamioka without marginalizing over ϵ_{ee} and $|\epsilon_{e\tau}|$, are also shown to show the contribution of these two parameters.

between δ_{CP} and $\arg(\epsilon_{e\tau})$ around a certain set of the two phases. Here we assume that the true oscillation parameters are

$$\begin{aligned}\bar{\epsilon}_{ee} &= 0.8, \\ |\bar{\epsilon}_{e\tau}| &= 0.2, \\ \bar{\phi}_{31} &\equiv \arg(\bar{\epsilon}_{e\tau}) = 0, \\ \bar{\delta}_{\text{CP}} &= -\frac{\pi}{2}.\end{aligned}$$

The allowed regions at 90% C.L., around the true value $(\bar{\delta}_{\text{CP}}, \arg(\bar{\epsilon}_{e\tau}))$ are shown in Fig. 4 for $(\bar{\epsilon}_{ee}, |\bar{\epsilon}_{e\tau}|) = (0.8, 0.2)$. To clarify the roles of the two detectors, in the case of the off-axis angle 1.3° , separate contours are given in Fig. 5 for the result from the detector in Kamioka, for that from the detector in Korea, and for that from the combination of the two. As we can see from Fig. 4, T2HKK at the off-axis angles 1.3° and 1.5° has good sensitivity also in the sensitivity to the CP phases. In the case of off-axis angle 1.3° , the sensitivity of T2HKK is better than that of DUNE. This can be explained as follows. The detector at Kamioka, which has a shorter baseline length, has poor sensitivity to the matter effect and therefore to ϵ_{ee} and $|\epsilon_{e\tau}|$. This is why the allowed region of the Kamioka detector is large in Fig. 5 (purple contour) since the uncertainty in ϵ_{ee} and $|\epsilon_{e\tau}|$ increases the uncertainty in the CP

phases. However, from the result of the detector in Korea, we have stronger constraint on ϵ_{ee} and $|\epsilon_{e\tau}|$. If we use this information, then the detector at Kamioka gives better sensitivity to δ_{CP} because of its high statistics. To confirm this, in Fig. 5, we also draw the contours for the Kamioka detector assuming ϵ_{ee} and $|\epsilon_{e\tau}|$ is known (the red dotted contours) and we see that the allowed region shrinks profoundly. So sensitivity of the combined T2HKK detector complex to the CP phases is better than that of DUNE. This synergy of the detectors at Kamioka and in Korea in the determination of the CP phases is the striking advantage of the T2HKK experiment. On the other hand, the HK atmospheric neutrino experiment has disjoint allowed regions particularly in the inverted mass hierarchy. If one assumes that HK could separate neutrinos and antineutrinos, then we have confirmed that these disjoint regions disappear. So we conclude that these disjoint allowed regions appear because HK cannot separate neutrinos and antineutrinos. However, since the HK atmospheric neutrino measurement cannot separate neutrinos and antineutrinos, as far as sensitivity to the CP phases is concerned, its performance is not as good the T2HKK experiment in inverted hierarchy.

IV. CONCLUSION

We have studied the sensitivity of the T2HKK experiment to the non-standard interaction in propagation with the ansatz (10). With the ansatz (10), we obtained the region in the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane in which T2HKK can distinguish NSI from the standard three-flavor scenario. As far as the sensitivity to NSI is concerned, T2HKK at the off-axis angle 1.3° is the best option, and with this option T2HKK can discriminate NSI at 3σ from the standard case for approximately $|\epsilon_{ee}| \gtrsim 1$ and $|\epsilon_{e\tau}| \gtrsim 0.2$. The sensitivity of DUNE is comparable as that of T2HKK with 1.3° off-axis flux configuration in normal hierarchy but it is better in the inverted hierarchy. We find that the sensitivity of the HK atmospheric experiment is the highest among the other setups considered in this work.

On the other hand, if the value of $|\epsilon_{e\tau}|$ is relatively large $|\epsilon_{e\tau}| \gtrsim 0.2$, then we can determine the two phases δ_{CP} , $\arg(\epsilon_{e\tau})$ separately by T2HKK or DUNE. As far as the sensitivity to the CP phases is concerned, T2HKK is the better than DUNE. The powerful feature of determination of the two CP phases is the remarkable advantage of the T2HKK experiment. The atmospheric neutrino experiment at HK is inferior to the two long-baseline experiments

in inverted hierarchy but superior in normal hierarchy.

Since the matter effect A and the baseline length L appears in the form of $AL/2 \sim L/4000$ km in the oscillation probability, long-baseline neutrino experiments with longer baseline lengths ($L \gtrsim 1000$ km) are sensitive to the matter effect. Hence they are also sensitive to NSI. The nice feature of the T2HKK experiment is that while the detector at Kamioka with a shorter baseline length is advantageous to measure δ_{CP} because of its high statistics, the one in Korea with a longer baseline length has better sensitivity to the matter effect as well as ϵ_{ee} and $|\epsilon_{e\tau}|$. We have seen that the sensitivity to ϵ_{ee} and $|\epsilon_{e\tau}|$ is the best at the off-axis angle 1.3° . Thus we conclude that T2HKK at the off-axis angle 1.3° is expected to be the best option to make the synergy of the two detectors effective determine the NSI parameters ϵ_{ee} and $|\epsilon_{e\tau}|$ as well as the CP phases δ_{CP} and $\arg(\epsilon_{e\tau})$.

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